8. A method and a set of apparatus for mineralogic-granulometric analysis with a microscope

By

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Contents

Introduction

A new set of apparatus and a method of analysis have been elaborated in order to facilitate the time-consuming and tiresome work involved in granulometric analysis of mineral grain distributions with the aid of a microscope. The following examinations can be performed with the apparatus:

1. Granulometric-mineralogic analysis of thin sections in which the particle sizes are measured as found in the section surface giving the volume frequencies of up to ten minerals or groups of minerals in the sample, further the grain-size distribution in volume frequency in the whole slide, and, finally, different grain-size distributions in volume frequency of up to eight minerals or groups of minerals in the slide.

2. Granulometric-mineralogic analysis of loose-grain mounts. This gives the grain-size distribution in the whole sample, and different grain-size distributions of up to eight minerals or groups of minerals in the mounts. The number

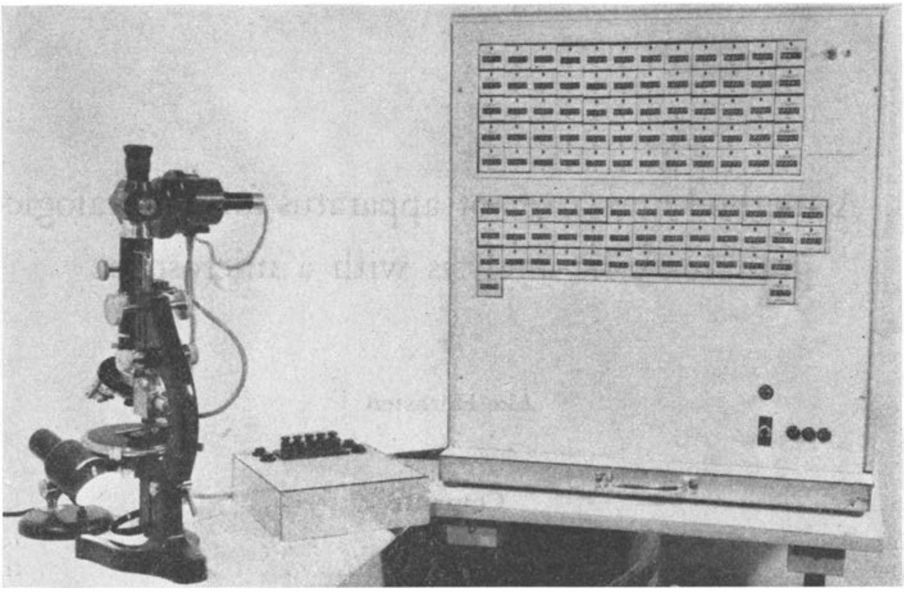


Fig. 1. The recorder with its keyboard and the microscope with the measuring-ocular.

frequency of particles of different minerals or groups of minerals are recorded in ten grain-size classes.

3. Examination of the shape and roundness of single mineral grains both in thin sections and in loose-grain mounts.

The apparatus consists of a polarization microscope of standard model with a newly-designed measuring-ocular which is connected with a recorder over a keyboard and an objective indicator. The thin section is brought by steps into the field of view of the microscope with a point-count mechanical stage. In thin sections the determinations of the frequency of the different grain sizes and minerals are performed according to the so-called point-count method. See Figs. 1 and 2.

The apparatus has been described previously in a preliminary report (HÖRNSTEN 1957).

Definitions of "grain size"

The grains in rocks and soils present very great variations of shape from e.g. thin mica scales to spheroidal quartz grains, and therefore the concept of grain size must be defined in some way in microscopic grain-size examinations. We shall not deal with the multitude of definitions of grain size that have been suggested for other methods of size analysis.

Grain-size determinations in a microscope only seldom permit the establishment of the three-dimensional extension of the grains. For routine purposes

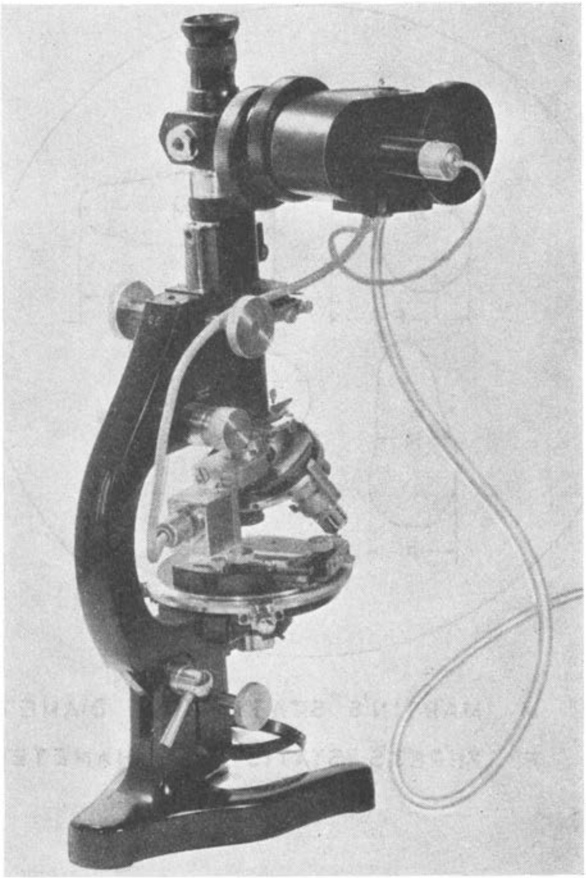


Fig. 2. The measuring-ocular is used together with a Leitz polarizing microscope CM with a revolving nosepiece with objective indicator attached to it.

one has to measure the projections of loose grains or grain sections in thin sections or polished specimens. Some of the definitions of grain size intended for determinations in a microscope may be presented in the following way:

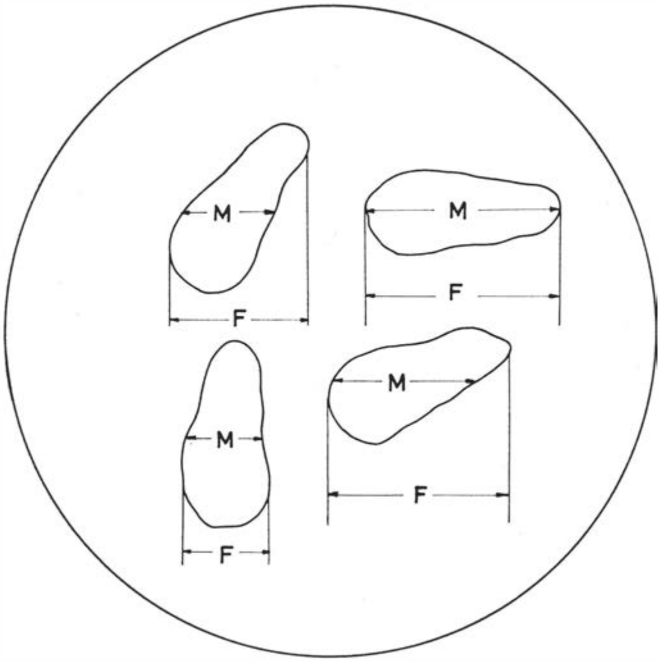
A. Univocal linear measures, which are independent of the orientation of the grain projections.

1. The *largest diameter*, l_p, is the distance between the two points on the grain situated at the greatest distance from each other.

2. The *middle diameter*, b_p, is the shortest possible distance of two points between which the projection of the grain can pass.

3. The *arithmetical mean* of the largest diameter and the middle diameter, $\frac{l_p + b_p}{2}$.

4. The *geometrical mean* of the largest diameter and the middle diameter, $\sqrt{l_p b_p}$.



M MARTIN'S STATISTICAL DIAMETER
F FERET'S STATISTICAL DIAMETER

Fig. 3.

B. Statistical linear measures. If the grain size is measured in these terms, a change in the orientation of the grain projections will result in different grain-size measures for one and the same grain.

1. *Martin's "statistical" diameter*, d_M, is the length of the line dividing the projected surface of the grain into two equal areas. The line is parallel to a given direction, e.g. the horizontal line of the ocular hair-cross reticle, Fig. 3. The division of the grain into two equal areas is carried out by estimation. (G. MARTIN *et al.*, 1923–1924.)

2. *Feret's "statistical" diameter*, d_F, is the distance between two parallel lines that touch the outer contour of the grain, and are parallel to a given direction, e.g. the vertical line of the ocular hair-cross reticle (L. R. FERET, 1931), Fig. 3. This type of "statistical" diameter was used e.g. by N. G. HÖRNER (1957) in a major study of sand fractions from the Gobi Desert and of till from the neighbourhood of Uppsala. The examination was made on loose grains, and HÖRNER has made extensive comparisons with the values he obtained by the use of this measure, by him called "inventory dimension", and other measures, e.g. the "nominal sectional diameter", see below.

3. The *maximum horizontal intercept* (W. C. KRUMBEIN 1935) is the maximum extension of a line that is limited by the contours of the grain, and is parallel to a given direction, e.g. the horizontal line of the ocular hair-cross reticle.

4. The *horizontal extension* of the grain along a certain given inventory line. Grain-size measures of this type were used by e.g. H. MÜNZNER and P. SCHNEIDERHÖHN (1953) and H. ROETHSLISBERGER (1955).

C. Measures based on the size of the projected surface of the grains.

1. The *nominal sectional diameter* or *projected diameter*, d_p, is the diameter of a circle the area of which corresponds to the projected area of the particle, when the latter is viewed in a direction perpendicular to the plane on which the particle rests with the greatest stability.

$$d_p = \sqrt{\frac{4\,A_p}{\pi}},$$

where d_p = the projected diameter and A_p = the projected area of the grain. This grain-size measure is influenced neither by the form nor the orientation of the particles, and was defined by H. WADELL (1935, p. 258 and 259). It is also called the "projected diameter", particularly in technical literature, cf. e.g. H. HEYWOOD (1937, p. 140), or the "diameter of the circle of equivalent area", H. HEYWOOD (1933, p. 387).

Choice of grain-size measure and type of scale

For the simultaneous analysis of volume frequencies of different minerals and different grain sizes in thin sections the point-count method of GLAGOLEV (1933) is used. In this the slide must not be moved laterally or vertically during the measuring of the grain, but is only allowed to rotate around the vertical axis through the inventory point, the cross-hairs. The measurements are greatly facilitated if the scale used in measuring the grain size can be moved at will within the field of view of the microscope. Such movement is possible in the newly-designed measuring-ocular. This also gives a freer choice between different grain-size measures.

The scale used was a circular light-field with continuously variable diameter. A scale of this form has the advantage that it can be used for measuring sizes as well as shape and roundness of mineral grains. In grain-size determinations one can use the nominal sectional diameter.[1] Among all other measures, preference is to be given to the nominal sectional diameter because of the increase in the moments of uncertainty, which is induced by any other two-dimensional measure due to the shape and orientation of the mineral particles.

[1] As pointed out already by W. C. KRUMBEIN (1935, p. 489), WADELL's definition of the nominal sectional diameter applies only to loose grains. For thin sections and polished specimens, where sections of grains are observed, KRUMBEIN proposed the term "virtual nominal sectional diameter".

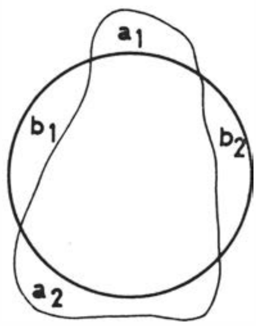


Fig. 4.

With the new measuring-ocular the size, position, colour, and light-intensity of the circular light-field can be varied at will so as to produce the best measuring conditions. The scale can also be brought rapidly to disappear altogether from the field of view, which may be advantageous in the identification of minerals. Measuring is carried out by placing the variable, circular light-field over the grain so that the grain surfaces falling outside the circle correspond to the surfaces within the circle that are not covered by the grain. Thus, in Fig. 4, $a_1 + a_2 = b_1 + b_2$. What is really measured is not the size of the grain, but the areas by which grain projection and circular field differ from each other. No figures are read off within the field of view of the microscope, but the dimensions are read outside the ocular on graduated scales, one for each objective magnification. Generally the apparatus is used for automatic grain-size recording; it is sufficient to adjust the scale and press a button. Thus, the grain size is recorded automatically in the correct grain-size class in the recorder, and this takes place independently of which objective is used on each separate occasion. The objectives, which are placed on an objective revolver, may be exchanged so that the most suitable degree of magnification can always be applied. An objective indicator then automatically performs the right connections in the recorder.

When the measuring-ocular is used for automatic grain-size recording, definite class limits must be used. For several reasons the class limits in the grain-size scale of J. A. UDDEN (1898) were chosen, among other things because the class limits may be expressed with phi-values, as was proposed by W. C. KRUMBEIN (1934). This greatly facilitates statistical calculations. The phi-value, ϕ, is the negative logarithm with the basis 2 for a grain size expressed in mm, or: the grain size expressed in mm $= 2^{-\phi}$. The following classes are distinguished in the automatic grain-size recording: >2; 2–1; 1–0.5; 0.5–0.25; 0.25–0.125; 0.125–0.062; 0.062–0.032; 0.032–0.016; 0.016–0.008; <0.008 mm. The corresponding class limits expressed in phi-values: >-1; -1–0; 0–1; 1–2; 2–3; 3–4; 4–5; 5–6; 6–7; $<7\ \phi$. In manual grain-size recording one can of course choose other class limits, if one finds it desirable.

Since the scale is round, it can also be used for the determination of length and breadth of grains according to different standards.

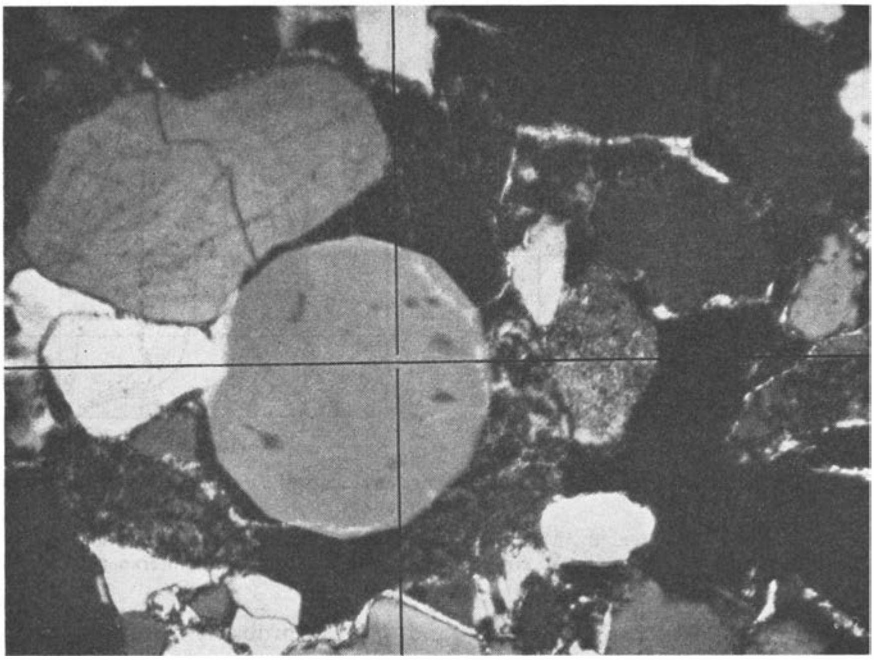


Fig. 5. Determination of the nominal sectional diameter. The scale is placed over a quartz grain, the light limit of which is partly discerned under the scale. The area of the grain accords with the area of the scale.

Earlier investigations using the nominal sectional diameter

Earlier the following methods of measuring the nominal sectional diameter have been used:

1. Reproduction of the individual grains with a camera, a microprojector, or a drawing apparatus, and exact measuring of the projected areas of the individual grains with the aid of a planimeter or the like, or estimation of the projected grain areas with the aid of comparison circles.

2. Projection on screens of the individual grains, and estimation of the projected grain areas with comparison circles arranged in various ways.

3. Estimation of the single projected grain area under the microscope with comparison circles of different kinds engraved in the ocular.

For this purpose various types of measuring-oculars have been designed. H. S. PATTERSON and W. CAWOOD (1936), G. L. FAIRS (1943), K. R. MAY (1945), R. J. HAMILTON *et al.* (1954) have proposed types that have frequently been used. R. MITSCHE and A. GRABNER (1953) have described a type of measuring-ocular in which network screens with different mesh sizes can be exchanged in the focal plane of the ocular. D. A. ROBSON (1958) has given an account of a type of measuring-ocular in the focal plane of which a series of circles with different diameters can be moved. ROBSON's ocular is intended for

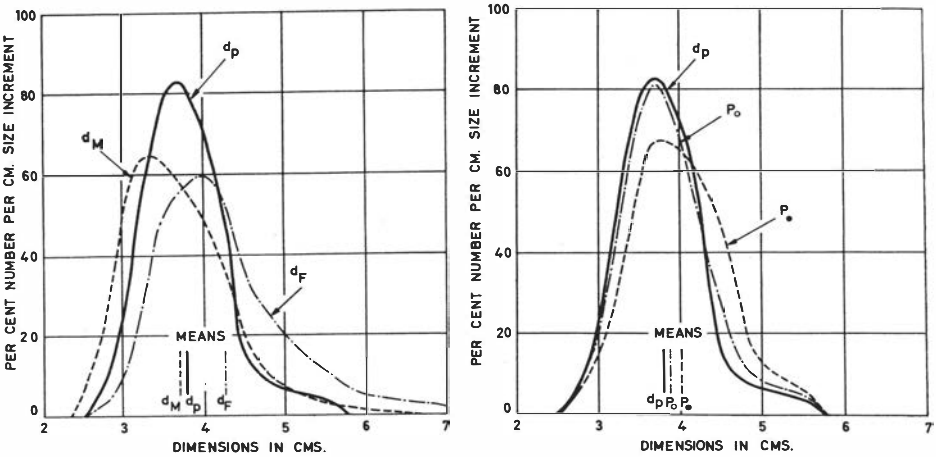


Fig. 6. Comparisons between different kinds of measurements of a grain-size distribution. From H. HEYWOOD (1946).

d_p Mean projected diameter. d_M Martin's statistical diameter. d_F Feret's statistical diameter. P● Comparison method using opaque circles. P○ Comparison method using transparent circles.

measuring the roundness of grains of sand, but can probably be used quite well for the determination of grain sizes.

A comparison between different methods of measuring particles in the microscope was made by H. HEYWOOD (1946). A large number of particles measured with a planimeter were remeasured under conditions similar to those in microscopic determination with the newly-designed measuring-ocular. Ten persons determined the grain-size distribution with Martin's and Feret's statistical diameters and with opaque and transparent comparison circles. The result of the investigation is perhaps best seen in HEYWOOD's diagram, Fig. 6. This permits the conclusion that the mean values obtained with Martin's statistical diameter and transparent comparison circles are rather close to the mean value obtained by exact measurement with a planimeter. The use of transparent comparison circles gives the smallest deviation from the frequency curve obtained by exact measurements with a planimeter. The modes show a high degree of accordance for the determinations made with comparison circles and with a planimeter. The use of comparison circles results in a slight tendency towards a general overestimation of the grain size, this tendency being slightly enhanced on the measurement of longitudinally extended grains with transparent comparison circles.

H. ALLING (1941) introduced a method of measuring grain sizes in a projection microscope. The measurements were taken on projected images of mineral grains with the aid of the projection of an iris diaphragm. He compared the values obtained by the estimation of the grain sizes according to this method with those obtained by exact determination of the particle areas with a polar planimeter. Measurement on 50 grains gave a maximum overestimation of 10%

and a maximum underestimation of 12.8% of the diameter. The arithmetical mean of the errors is only +0.32%. The errors due to overestimation and underestimation thus compensate each other to a great extent.

F. ENDTER and H. GEBAUER (1956) have designed an apparatus for particle size analysis on transparent photographic enlargements of specimens. A reference circle, the aperture of a diaphragm, is projected onto the back of the enlargements. Measuring is carried out by adjusting the size of the reference circle so as to agree in size with the particle. For this purpose an adjusting wheel is provided. Semi-automatic recording of the particle sizes is made possible by means of electrical counters and a contact device connected with the adjusting wheel. According to a ZEISS pamphlet No. 34–901–d, the apparatus is manufactured by CARL ZEISS under the name "Teilchengrössen-Analysator nach Endter".

N. G. HÖRNER (1957, p. 24) has compared the nominal sectional diameter with some other grain-size measures, e.g. with Feret's statistical diameter (HÖRNER's inventory dimension). In HÖRNER's investigation the arithmetical mean for Feret's statistical diameter lies about 8% above the mean value of the sectional diameter. In HEYWOOD's investigation it is about 12% higher than the mean value of the sectional diameter.

The newly-designed measuring-ocular has the great advantage of providing a comparison circle that is in the centre of the field of vision, and can be placed over the grain to be measured without moving the slide. If the comparison circles are at a distance from the grains to be measured, the measuring errors are easily increased. H. H. WATSON and D. F. MULFORD (1954) have investigated such measuring errors and their variation for different persons.

In the examination of loose-grain mounts it is of value to know the ratio between the nominal sectional diameter and the sieve aperture which a particle can just pass through. This ratio was studied by H. HEYWOOD (1947, p. 19) for particles with different length/breadth and breadth/thickness proportions. HEYWOOD states that for particles of the most common shapes the nominal sectional diameter is about 1.4 times the equivalent sieve aperture.

The design of the measuring-ocular

The body of the newly-designed measuring-ocular consists of a so-called Kellner ocular with a composite achromatic eye-lens, Fig. 7 (a), and a field lens, Fig. 7 (b). The focal plane is below the ocular lenses, a fixed hair-cross reticle is provided in the focal plane, Fig. 7 (c). This constructional unit functions as an ordinary ocular of the positive type, and gives 12 times' ocular magnification. The focusing on the cross-hairs is achieved by turning the eye-lenses which have a diopter adjustment of ±5 diopters.

For the use of the ocular as a measuring-ocular a reference circle of variable size is projected into the focal plane, an iris diaphragm with 12 steel blades,

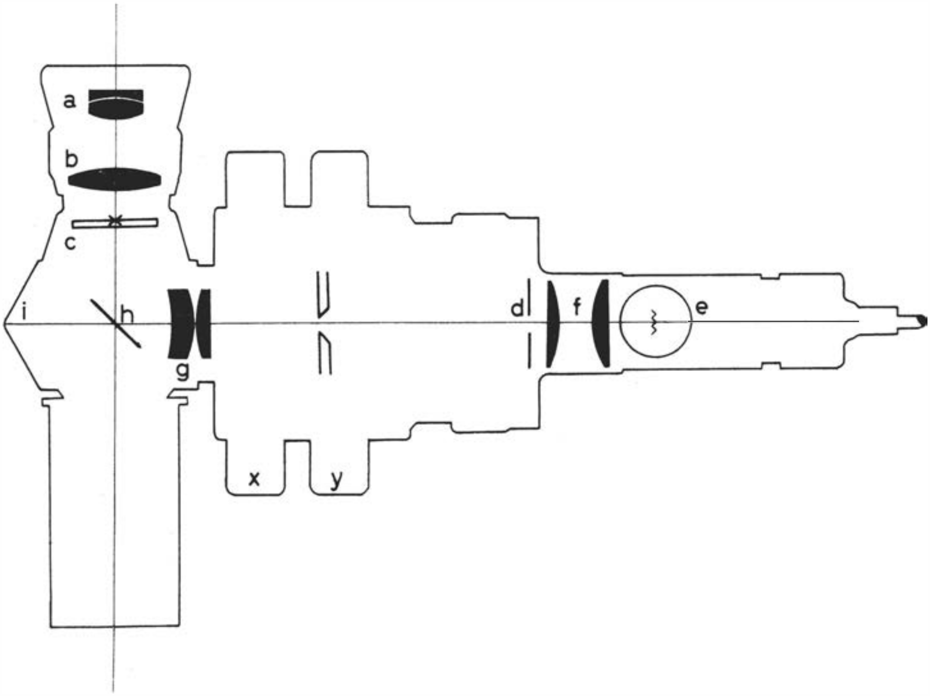


Fig. 7. The optical construction of the measuring-ocular.

Fig. 7(d), being used for this purpose. The size of the diaphragm aperture can be altered so that the maximum aperture, 25 mm, is about 17 times the minimum one. The minimum diameter of the reference circle is 1/18 of that of the field of view of the microscope, and its maximum diameter somewhat smaller than the diameter of the field of view. The diaphragm aperture is not strictly circular, but forms a dodecagon with curved sides. The large number of laminae makes the deviations from the circular form comparatively small, and in the case of large diaphragm apertures they are practically negligible. In the case of a full diaphragm aperture the reference opening is a perfect circle, the radius of the curved sides of the laminae equalling the radius of the largest diaphragm aperture. The rotation of the diaphragm-control gear produces an almost linear change of aperture.

In the field of view of the ocular the reference or measuring circle appears as an illuminated area. An electric lamp, Fig. 7(e), illuminates the iris diaphragm, (d), through two condensor lenses, (f). This is effected by the projection lenses, (g), projecting the image of the diaphragm into the focal plane of the ocular. This is effected by the reflexion of the bundle of rays by an obliquely fixed comparison plate, (h). The latter is a plane parallel, transparent and anti-reflexion coated glass plate. The rays that come from the diaphragm and pass the comparison plate without being reflected upwards are caught in a so-called light-trap, (i).

The rays of light that come from the thin section through the objective pass the oblique anti-reflexion coated comparison plate without great losses of intensity. This makes it possible simultaneously to observe in the ocular both the scale, i.e. the image of the diaphragm, and the specimen.

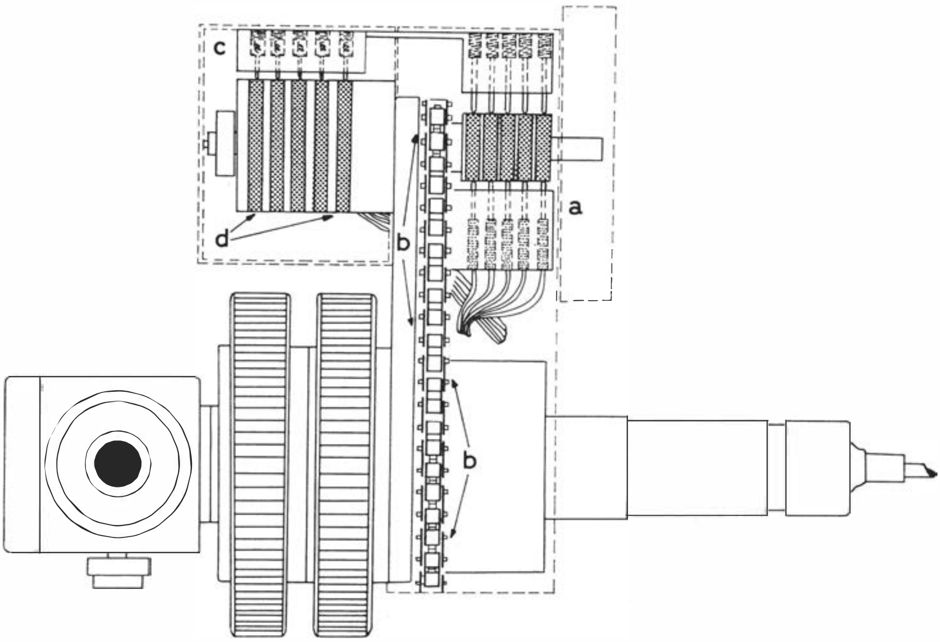
For several reasons it must be possible to vary the intensity of light on the circular field of light serving as scale. For this purpose the intensity of light of the incandescent lamp, (e), is adjusted by means of a rheostat. The luminosity of the specimen may vary considerably from one point to another. A change of the degree of magnification (change of objective) also demands a change in the intensity of light of the scale. The scale should be seen as a barely perceptible circular illuminated field over the object to be measured.

Also the colour of the scale can be changed by the insertion of suitable colour filters in a slot between the condensor lenses.

In measuring, the scale can be moved conveniently in the x- and y-directions in the field of view of the microscope by the rotation of two knobs, Fig. 7 (x) and (y). Rotation of one of the knobs makes the scale oscillate forwards and backwards in the x-direction. The rotation is never-ending. On the rotation of the other knob the corresponding movement takes place in the y-direction. These movements are effected by action of the knobs upon excentric bushes. With this contrivance the scale can rapidly be moved to the desired position anywhere within the field of view without moving the specimen.

The size of the scale is changed by turning a knob, Fig. 8 (a), connected with the control lever of the iris diaphragm over a gear-chain transmission, (b), with a suitable gear ratio. The control lever of the iris diaphragm can be swung through 90° only, yet the gearing permits rotation of the knob by about 270°. Simultaneously with the knob a cylinder, (c), is turned, which has one graduation for every objective. On these graduations the size of the scale in the field of view of the microscope can be read off directly in mm or μ, and no recalculation has to be made for different degrees of objective magnification. The various graduations have been calibrated with the aid of a stage micrometer.

When the measuring-ocular is used for semi-automatic recording of grain sizes, a contact contrivance in the cylinder is utilized, Fig. 8 (d). Contact fields, one for each degree of objective magnification, are divided into various sectors corresponding to different grain-size classes. Rotation of the control knob of the diaphragm moves a series of contact pins over the various contact fields. For the recording of a certain grain-size first a suitable degree of magnification is chosen. Subsequently the size of the scale is adjusted so as to correspond to the size of the grain. A contact on the keyboard is depressed, and a current is transmitted by the objective indicator to the contact sector that corresponds to the degree of magnification and the scale size used. The size of the grain is then recorded in the adequate grain-size class.



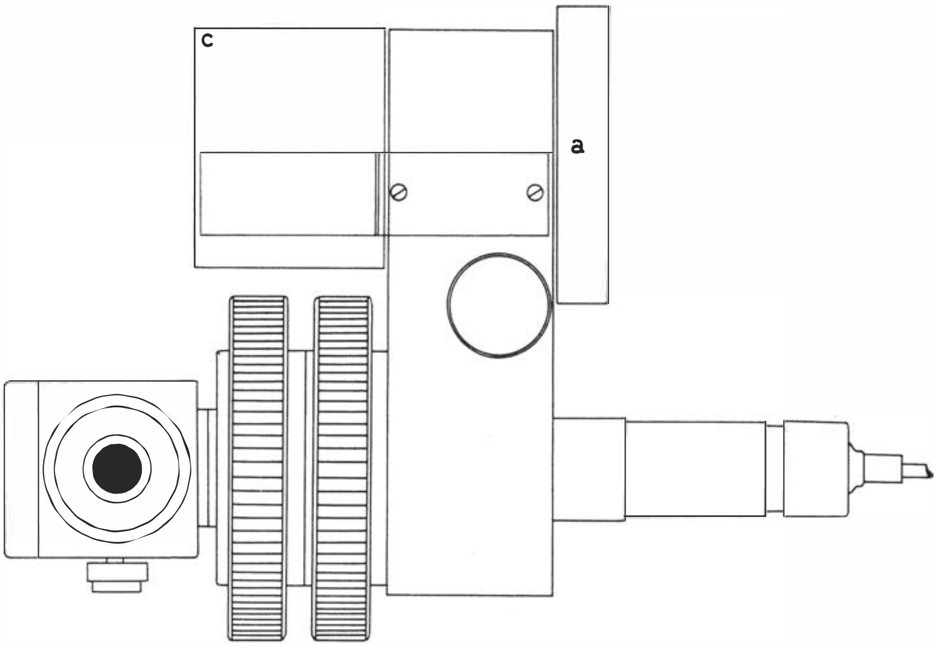


Fig. 8. The measuring-ocular, seen from above.
In the upper picture the contact arrangement is exposed.

GLAGOLEV'S point-count method and its application to combined mineralogic-granulometric analysis of thin sections

In the simultaneous volume frequency analysis of grain sizes and mineral contents in thin sections and polished specimens, the method invented by A. GLAGOLEV (1933, 1934) for quantitative analysis of various mineral frequencies in thin sections and polished specimens is used. This method,[1] which has come into increasing use in recent years, is called the point-count method.

In order to ensure that the theoretical conditions are valid, the measuring must take place in an exactly defined inventory plane, in this case the upper surface of the thin section of 0.03 mm thickness. A great number of inventory points are distributed regularly over a thin section in such a way that the thin section is moved by steps, and the mineral content recorded in the points coinciding with the cross hairs. The volumes of the various minerals are taken to correspond to the surfaces of the respective minerals on the upper surface of the thin section and consequently also to the number of inventory points that have fallen on the respective minerals. A. GLAGOLEV (1933), F. CHAYES (1949, 1950*a*, 1955), T. DAHLLÖF (1952), M. ROSENFELD (1954), I. H. FORD (1954), J. LAMPRECHT (1954), and others have designed various mechanical devices on the mechanical stage of the microscope in order to achieve equally-spaced movement of the specimen, and thus the desired symmetrical point net upon the specimen. A. HENNIG (1957*a*) has suggested a measuring-ocular with 25 regularly distributed inventory points. This measuring-ocular is very useful in analysis of specimens that can be kept fixed during the time needed for the analysis of an entire field of view. In the analysis of thin sections of rocks rotation of the stage with the specimen is often necessary for the identification of the minerals. Often the objective has to be changed in order to obtain the suitable degree of magnification, and this produces changes in the point net over the preparation. These circumstances restrict the use of the point-net ocular in petrography.

A. GLAGOLEV (1934) gives the probable error for the point-count method, P.E._{tot}, expressed in per cent as

$$\text{P.E.}_{\text{tot}} = 0.6745 \sqrt{\frac{A(100-A)}{n}},$$

where A is the percentage of a component and n the number of points counted.

The probable error for a certain component, P.E._{rel}, expressed in per cent of the frequency of the component will then be

$$\text{P.E.}_{\text{rel}} = 67.45 \sqrt{\frac{100-A}{nA}},$$

[1] In quantitative investigations for purposes of plant sociology, a point-count method has been used since the beginning of our century. For this, see the survey in G. E. DU RIETZ (1930) and also B. LINDQUIST (1931).

where A is the frequency of the component in per cent and n the number of points counted.

For the rapid calculation of the probable errors for various component frequencies and various numbers of points counted one can use, with some modification, the nomograms designed by G. RITTENHOUSE (1940). For the calculation of the $P.E._{rel}$ one can use, with some modification, A. L. DRYDEN's rather summary diagram reproduced in W. C. KRUMBEIN and F. J. PETTIJOHN (1938, p. 472). The theoretical and practical conditions of the point-count method have been dealt with in detail in several works by F. CHAYES (particularly 1956) and A. HENNIG (1957*a* and 1958), and others.

The areas of the different components in the inventory plane, i.e. the upper surface of the thin section, correspond to the volumes of the respective components. This is valid irrespective of whether the word "component" is taken to signify different minerals or different grain sizes. The point-count method can therefore be used also in grain-size analysis in thin sections and it permits simultaneous analysis of mineral distributions and grain-size distributions.

For granulometric analysis of very coarse-grained materials N. G. HÖRNER (1944, 1946, 1947) has worked out a point-count method on the same basis as that of GLAGOLEV. HÖRNER's point-count method has been reviewed in international geological literature by A. CAILLEUX (1947*a*, p. 101) and J. P. PORTMANN (1956). The volume frequency of different groups of particle sizes simply corresponds to the number of inventory points that have coincided with particles in different groups of grain size.

The principles of HÖRNER's point-count method have been applied here to granulometric analysis of thin sections. The method has the advantage of providing inventory points that admit of simultaneous analysis of different mineral frequencies and different grain-size frequencies. The degree of magnification can be changed freely, the stage can be rotated, and the other advantages of the petrographic microscope can be utilized unimpededly. The method can furthermore easily be combined with automatic recording procedures.

Methods for volume frequency determination of grain sizes and mineral contents in thin sections and polished specimens

In investigations of grain sizes in thin sections, measurements are taken on sections of grains of varying size and shape. As the result of the sectioning effect the observed size of a grain in the section and its real size very seldom agree. A large number of methods for the determination of grain-size distributions in thin sections and polished specimens with the aid of a microscope have been worked out earlier, as well as calculation methods for the elimination of the sectioning effect: T. HAGERMAN (1924), S. D. WIKSELL (1925, 1926), E. SCHEIL (1931, 1935), E. SCHEIL & H. WURST (1936), W. C. KRUMBEIN (1935, 1950),

W. Brückner (1938), N. Odemark (1947), M. Vuagnat (1949), R. Dederichs and H. Kostron (1950), F. Chayes (1950*b*, 1951), N. N. Greenman (1951*a*, 1951*b*), C. R. Pelto (1952), M. Rosenfeld, L. Jacobsen and J. Ferm (1953), A. Hennig (1957*a*, 1957*b*, 1958).

For the analysis of distributions of different minerals in different grain-size classes, R. Helmbold (1952) has utilized a modification of A. Rosiwal's (1898) method for planimetric analysis. In an inventory plane the areas of the different components correspond to the volumes of the respective components. After having laid a series of inventory lines across the thin section, one examines how much of the inventoried length is occupied by the different components. The length ratios for the different components then correspond to the areal proportions of the components and, consequently, also to the volume proportions of the different components. As a measure of grain size Helmbold used the length of the chord formed by the inventory line in each grain. In order to avoid very long inventory lines Helmbold performed the measurings by steps, one for each grain-size class, until a sufficient number of grains had been measured for each grain-size class.

For the determination of grain-size distributions in volume frequency in thin sections H. Münzner and P. Schneiderhöhn (1953) have proposed a chord-measuring procedure, "Sehnenschnittverfahren". According to this method an inventory line is laid across the grains in the thin section, the chords formed by the inventory line across the different grains being measured with a micrometer ocular. At least one thousand chords are measured, and grouped in different size classes. The calculation of the probable grain-size distribution in the rock sample from which the thin section has been prepared is then performed with the help of correction formulas (H. Münzner, 1953).

G. H. Packham (1955) has suggested the following method for the planimetric analysis of the grain-size distribution. The thin section is displaced with an integrating stage, the various revolving drums of which correspond to different grain-size classes. As a measure of grain size Packham uses the middle diameter in order to get class accordance with such values as are obtained by sieving analysis. When a grain reaches the cross-hairs, and is to be recorded, the grain size is first determined with a micrometer ocular. The drum corresponding to the grain size is turned, and thereby the preparation is moved until the cross-hairs leave the grain. From the measured values probable grain-size distributions can be calculated with the aid of correction formulas.

A. Vistelius (1958) has criticized Packham's method, and suggested certain improvements.

By means of a point-count mechanical stage H. Roethlisberger (1955) regularly distributes points along an inventory line that forms chords over the different grains in the thin section. The lengths of the individual chords are measured, and for each inventory point one chord is taken into the calculation. The chords are distributed over different size classes, and the probable grain-

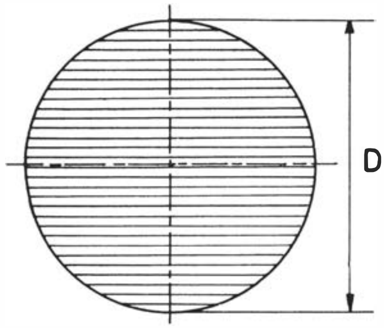


Fig. 9.

size distribution in volume frequency can then be calculated with the aid of correction formulas on the basis of the number of chords in different size classes.

G. FRIEDMAN (1958), finally, has elaborated a calculation method that gives good agreement between the values obtained in sieving analysis and such values as are obtained by analysis of thin sections. He has also made comparisons with calculation methods proposed earlier.

On account of the so-called sectioning effect the size of a grain observed in the thin section very seldom agrees with the real size of the grain. The study of the sectioning effect was taken up first by T. H. HAGERMAN (1924) and S. D. WICKSELL (1925, 1926), and later investigations of this problem have been carried out, amongst others, by W. C. KRUMBEIN (1935).

According to N. ODEMARK (1947) the influence of the sectioning effect can be exemplified in the following way. A sphere with the diameter D is divided into a very great number, n, of thin spherical zones with the thickness h. The sum of the mean diameters of the spherical zones is called S_d, and the arithmetical mean of the different mean diameters of the zones is called d_m. See Fig. 9. This gives

$$n\,d_m = S_d, \quad h = D/n, \text{ and } D\,S_d/n = \pi D^2/4.$$

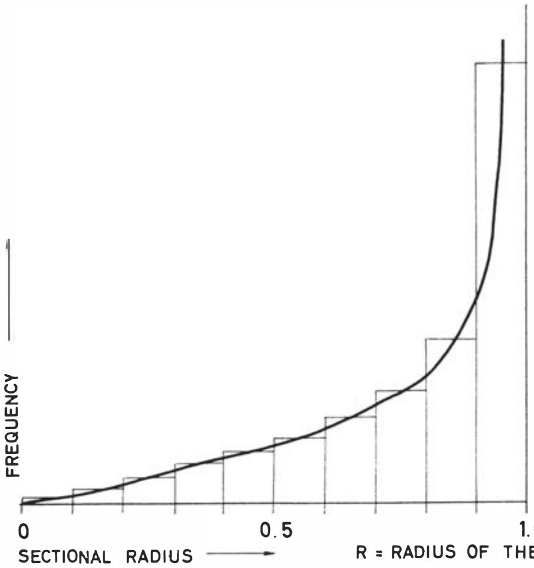
From this follows that

$$d_m = \pi D/4 = 0.785\ D, \text{ and } D = 4\,d_m/\pi = 1.273\ d_m.$$

The median slice lies at the distance $R/2$ or $D/4$ from the centre of the sphere. The diameter of the median slice, d_{md}, is obtained by calculating the sides of the right-angled triangle in the sphere with the sides $d_{md}/2$, $D/4$, and $D/2$.

$$d_{md} = \sqrt{3\,D^2/4} = 0.866\ D.$$

Thus, if a large number of spheres with the diameter D are distributed at random in an embedding substance of which a very thin section is prepared, diameters from D down to infinitely small sizes will be observed upon the surface of the thin section. The arithmetical mean of the observed section a



b

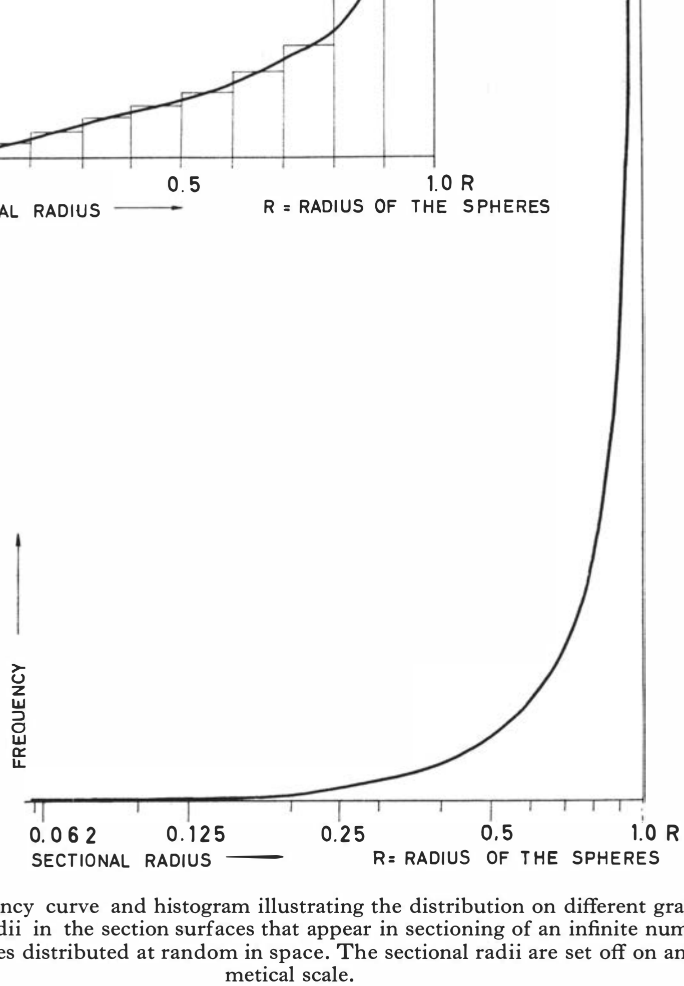


Fig. 10 a. Frequency curve and histogram illustrating the distribution on different grain-size classes of the radii in the section surfaces that appear in sectioning of an infinite number of equal-sized spheres distributed at random in space. The sectional radii are set off on an arithmetical scale.

Fig. 10 b. The same distribution as in Fig. 10 a, but the sectional radii are set off according to a logarithmic scale.

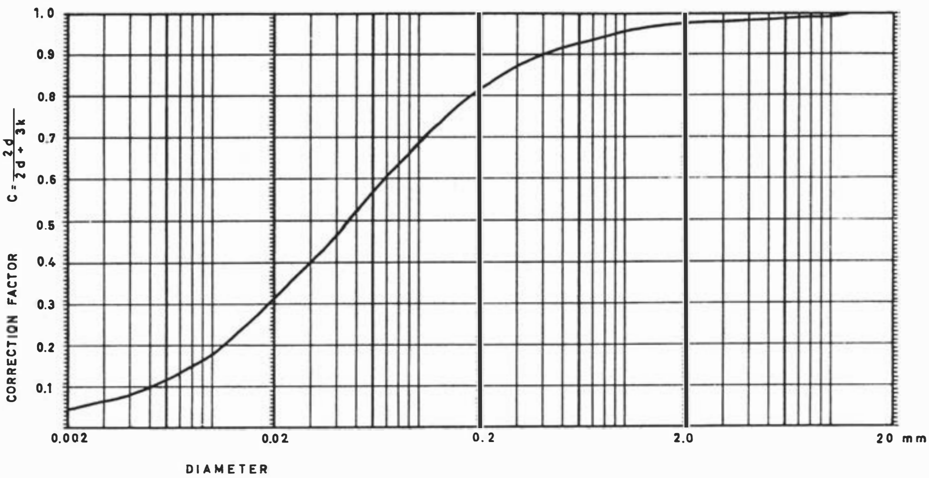


Fig. 11. Diagram of F. CHAYES's correction factor for elimination of the over-representation of opaque spheres in a transparent medium in transmitted light. *d* diameter of the opaque spheres. *k* standard thickness 0.03 mm.

diameters, d_m, is 0.785 D, and the section diameter of the median is $d_{md} = \sqrt{3}\,D/4 = 0.866\,D$. A probability function describing the distribution of the section radii resulting from the sectioning of spheres of identical size was established by T. H. HAGERMAN (1924) and subsequently by W. C. KRUMBEIN (1935):

$$P(x)\,dx = \frac{1}{R}\left(\frac{x}{\sqrt{R^2 - x^2}}\right) dx,$$

where R is the radius of equal-sized spheres and x is the section radius. The relative frequency of section radii falling into the interval between x_1 and x_2 is obtained by integration between the limits x_1 and x_2. A diagram illustrating the distribution of the different section radii over different size classes is given in Fig. 10*a*. There the radii are set off according to an arithmetical scale. Generally a logarithmic scale is used in sedimentary petrography for grain-sizes. If the section radii are set off according to a logarithmic scale a distribution of the type seen in Fig. 10*b* is obtained.

In analysis of opaque minerals with small grains the so-called HOLMES effect may cause considerable errors in the estimation of mineral frequencies as well as of grain sizes. For technical reasons the thin section must be prepared to a standard thickness of 0.03 mm. Various spherical particles will then be represented in the thin section by spherical segments and zones if the various sphere diameters are greater than 0.03 mm. In the planimetric analysis it is presupposed that the measurements are taken in a definite inventory plane, viz. the upper surface of the thin section. Owing to the thickness of the thin section the opaque grains will, however, not be represented by their true inventory section in transmitted light, but the projections of their maximal extensions in the thin section from the lower to the upper surface of the latter. The influence of this source of error grows rapidly with decreasing grain size. For spherical opaque particles with the diameter 0.12 mm the over-representation is 37.5 %, for opaque grains with the diameter 0.012 mm it is 850%. F. CHAYES (1956, chapter 11) has introduced a correction factor for this source of error, and the diagram in Fig. 11 has been drawn on the basis of his Table 11.1. In analyses the influence of the HOLMES effect can be eliminated to a great extent, at least in cases of large grain sizes, by the use of incident light, giving reflexes on the section surfaces of the opaque grains. It is then possible to distinguish what are section surfaces, and what are projections of grains.

According to R. B. ELLIOT (1952) an effect resembling HOLMES effect can appear, when transparent grains of widely differing refractive indices border one upon another.

The principles of recording with the new recorder

The recorder is built up of 100 electrical counters which are connected with each other in various ways, and controlled from a keyboard with 14 keys. See Fig. 12 with the appended explanation of symbols.

In the analysis of thin sections as described above, the point-count method is used for the combined mineralogic and granulometric analysis. With a point-count mechanical stage the specimen is moved by steps, and the ocular cross-hairs fall on different, regularly distributed inventory points. For each inventory point is recorded on what mineral and on what grain size the point in question is located. The recording is carried out in the following way. First one identifies the mineral under the cross-hairs, and depresses the key corresponding to this mineral on the keyboard. Then a transposition key is depressed as a matter of routine to adapt the instrument for the next recording moment. The grain size is determined with the measuring-ocular, and in automatic grain-size recording the depression of a key on the keyboard is all that is needed for the automatic recording of the grain in the correct grain-size class. If, on the other hand, manual grain-size recording is used, the grain size is read off on the outside of the ocular, and the key on the keyboard corresponding to the grain size is depressed. On termination of the recording a resetting key is depressed as a matter of routine, and the apparatus is ready for recording once again.

Ten different minerals or groups of minerals can be recorded. Each mineral has a counter for the inventory points that have fallen on the mineral in question. These counters are situated in a vertical row to the extreme right, and are marked Σpx, Σpa, Σpb, etc. A counter Σp adds up the number of inventory points that have fallen on different minerals, i.e. it gives the sum total of the values recorded by the counters Σpx, Σpa, Σpb, etc. From the counters just

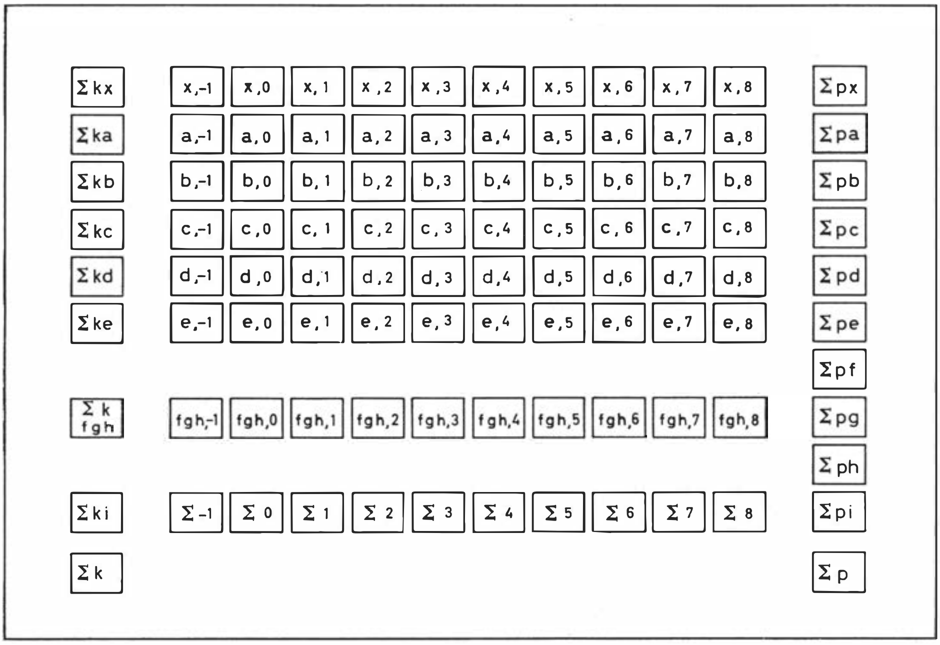


Fig. 12. Plan of the recorder with the counters. The single counters are indicated by squares. The functions of the individual counters are seen from the marks drawn in the squares. Σ = summation sign. p = points. x, a, b, c, etc. = abbreviations for different minerals. The symbol x is used for polymineral particles. -1, 0, 1, 2, etc. = abbreviations for different grain-size classes. The abbreviations indicate the lower class limit in each class in a ϕ-value. This does not apply to 8 which is an open-ended class. Σka = the sum of all recorded grains of the mineral a. Σpa = the sum of all recorded points upon the mineral a. Σk = the total sum of all recorded points upon all grains. a,0 = counter for the mineral a and the grain-size class 0. $\Sigma 2$ = the sum of the recordings in the grain-size class 2.

mentioned we obtain the volume frequencies of the different minerals in analysis of thin sections.

To the extreme left we have a row of eight counters, Σkx, Σka, Σkb, etc., recording points that have fallen on grains of the mineral x, on grains of the mineral a, etc. A counter Σk adds up all the recordings in these counters. In normal cases the recordings in Σka, Σkb, Σkc, etc. agree with the recordings in Σpa, Σpb, Σpc, etc. It is only in recordings of polymineral particles (see below) that there appear differences between the counters in the row farthest to the left and those in the row farthest to the right. The vertical row of counters farthest to the left gives the frequencies of points that have fallen on grains of different kinds, whereas the vertical row farthest to the right gives the frequencies of points that have fallen on minerals of different kinds.

For each mineral or group of minerals there exists furthermore a horizontal row of 10 counters, one counter for each grain-size class. These counters are marked x, -1; x, 0; x, 1; etc. (phi values). They give the distribution of the minerals over different grain-size classes in volume frequencies. For each grain-size class there is a summation counter, $\Sigma -1$; $\Sigma\ 0$; $\Sigma\ 1$; etc. These counters $\Sigma -1$, $\Sigma\ 0$, $\Sigma\ 1$ etc. give the volume frequencies of the different grain-sizes in analysis of thin sections.

In order to save counters, the minerals f, g and h have separate counters for mineral frequencies, Σpf, Σpg, Σph, but a common row of counters for grain-sizes: $fgh, -1$; $fgh, 0$; $fgh, 1$; etc. These counters are used, when the volume frequencies of the minerals f, g, and h are wanted separately, and when at the same time no more than a common grain-size distribution for these minerals is needed. Non-identifiable transparent minerals, non-identifiable opaque minerals, or "other minerals" may be referred to this group.

The volume frequency of the mineral i is read on the counter Σpi, but the grain-size distribution of the mineral i does not appear in a special row of counters, and the recordings of this mineral in different grain-size classes are made directly on the summation counters $\Sigma -1$, $\Sigma\ 0$, $\Sigma\ 1$, etc. The grain-size distribution of the mineral i will then be the difference between the total grain-size distribution in the sample and the grain-size distribution of the other minerals. Non-identifiable minerals or "other minerals" may be referred to the mineral "i".

The different counters are connected with each other in several different ways, and it will be simplest to explain the functioning of the recorder by a concrete example. When the inventory point (cross-hairs) has fallen on a grain of the mineral a and the grain size 1, the procedure is as follows. The following keys are depressed in turn: the key for the mineral a, the transposition key, the key for grain-size recording, and the resetting key. Thereby the counter $a, 1$ is switched on in the recorder. At the same time Σpa, Σp, $\Sigma\ 1$, Σka, and Σk function automatically. The following has then been recorded: one point on the mineral a in the grain-size class 1 in the counter a, 1, one point on the mineral a in Σpa, and one summation of the counted point in Σp, one summation of the counted point in the grain-size class 1 in $\Sigma\ 1$, one point on a grain of the mineral a in Σka, and finally the addition of the counted point on a grain in Σk.

The problem of recording particles consisting of several different minerals, here called polymineral particles, has been solved thus: the polymineral particles are referred to a special row of counters, $x, -1$; $x, 0$; $x, 1$; etc., and in these counters the frequencies of the polymineral particles are recorded in different grain-size classes in the usual way. The number of points that have fallen on polymineral particles is seen from the counter Σkx which is connected with the summation counter Σk. The vertical row farthest to the left then gives the frequencies of points that have fallen on grains of different kinds. When the recorder is used for recording polymineral grains, a connection between the counters Σpx and Σp is cut with a circuit-breaker. Points that have fallen on different minerals in the polymineral particles are recorded separately by the counters of points on the respective minerals, Σpa, Σpb, Σpc, etc. This can be done by depressing a special key for separate mineral recording and then the key for the mineral in question. The vertical row of counters farthest to the right will then give the volume frequencies of the different minerals. The proportion of e.g. the mineral *a* contained in polymineral grains is obtained from the recordings in Σka and Σpa and the difference between the recordings in Σka and Σpa.

In some rocks one particular mineral may be very abundant, e.g. quartz in quartzites. In analyses of such rocks the cross-hairs will repeatedly fall on the same mineral. In order not to have to depress the key of this mineral for each new recording, the apparatus has been designed so that after the first pressing down of the key for this mineral the apparatus is prepared for continued recordings of the same mineral. For each successive subsequent recording on this mineral it is sufficient to determine only the grain size, and depress the grain-size key. The recording of this mineral and the determined grain size is then effected each time by the depression of only one key, that of grain-size recording. Only when the inventory point falls on another mineral (or on a polymineral particle) one has to depress first the resetting key and then the key for the new mineral.

In order to get an idea of the variations within each thin-section sample one can write down the figures in the different counters or still better, photograph them for every hundredth recording, for every traverse, or for every group of traverses made with the mechanical stage.

In the analysis of loose-grain mounts the apparatus can be used for recording the number of grains of different minerals in different grain-size classes.

The apparatus can of course be used for grain-size recording alone or for mineral frequency recording alone in thin sections as well as in loose-grain mounts.

Measurings of shape and roundness with the new measuring-ocular

With the newly-designed measuring-ocular it is possible to measure the shape and roundness of mineral grains in thin sections or loose-grain mounts. Such measurements are possible, since the scale, the circular light-field, can be varied as to size as well as position. In measuring shape and roundness according to earlier methods each particle had, as a rule, to be represented by drawing or photographing, the measurements being taken on the pictures. This procedure has made the measuring a tedious work.

H. WADELL (1933, 1935) has proposed the following definition for two-dimensional sphericity, ϕ, of loose particles resting in the most stable position:

$$\phi = \frac{d_p}{D_c},$$

where d_p is the nominal sectional diameter and D_c the diameter of the smallest circumscribed circle. The values of d_p and D_c are without difficulty obtained

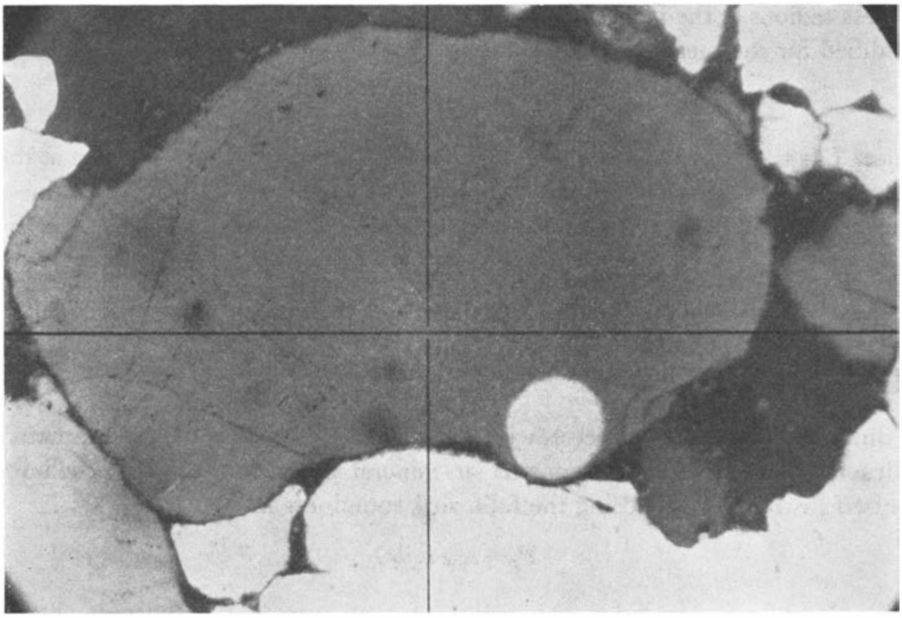


Fig. 13. The measuring-ocular can be used for rapid determination of the shape and roundness of mineral grains. Here the radius of the scale corresponds to the radius of curvature in the corner of the quartz particle.

with the measuring-ocular, and the proportions between d_p and D_c are easily calculated with a slide-rule. The recording of the distribution of the degrees of sphericity in different grain-size classes or in different minerals can then be done on a paper or with the aid of the recorder.

The determination of d_p involves a certain amount of subjective estimation. N. A. RILEY (1941) has proposed a definition of two-dimensional sphericity, ϕ_0:

$$\phi_0 = \sqrt{D_i/D_c},$$

where D_i and D_c are the diameters of the largest inscribed and of the smallest circumscribed circle, respectively, for the particle. The sizes of D_i and D_c can be measured exactly. The sphericity values according to this definition are about the same as the sphericity values according to WADELL's definition (in the case of ellipses they are identical).

Several roundness indices can be measured. The greatest amount of work is involved in the measuring of H. WADELL's (1932) roundness index, P_W:

$$P_W = \frac{\sum r/R}{N},$$

where r are the radii of curvature in the different corners, R the radius of the largest inscribed circle in the grain, and N the number of measured corners.

Less tedious is the determination of A. CAILLEUX's (1947 *b*) roundness index modified for the measuring of grain projections:

$$P_C = 2r_1/L,$$

where L is the greatest length of the grain, and r_1 the radius of curvature at the sharpest corner. It is also simple to measure PH. H. KUENEN's (1956) roundness index, P_K, modified for the measuring of grain projections:

$$P_K = 2r_1/b,$$

where r_1 is the radius of curvature at the sharpest corner, and b the largest diameter of the grain measured at right angles to the longest diameter of the grain.

Since most abrading processes in water tend to produce an approximately ellipsoidal shape of rock fragments or mineral particles the author believes himself justified in proposing the following roundness index P_H:

$$P_H = r_1 2L/b^2.$$

With this roundness index the radius of curvature at the sharpest corner, r_1, in a grain with the greatest length L and the greatest breadth b measured at right angles to L is compared with the radius of curvature in the terminal point of the major axis of an ellipse with the axes L and b. The radius of curvature in the terminal points of the major axis of an ellipse with the axes L and b is $b^2/2L$.

Description of the electrical construction and function of the recorder

The recordings take place in electrical counters, pulse counters, which are connected with each other in various ways as described above, cf. Fig. 12. By a system of electromagnetic relays a current is fed into the circuits that are needed for the desired recordings. The apparatus is controlled from a keyboard with 10 keys, common to minerals and grain-sizes, a transposition key M, a resetting key A, a grain-size recording key K, and finally a key for separate mineral recording S. These keys with the exception of K are found on the extreme left of the circuit diagram, Fig. 14.

The apparatus is run on 24 V D.C. supplied by a rectifier and a transformer connected to the 220 V A.C. mains.

Relays

The types of relays used are the standard models of the Swedish Telecommunications Administration. Such a relay consists of an electromagnet with an armature that is drawn to the magnet, when a current is passed through the

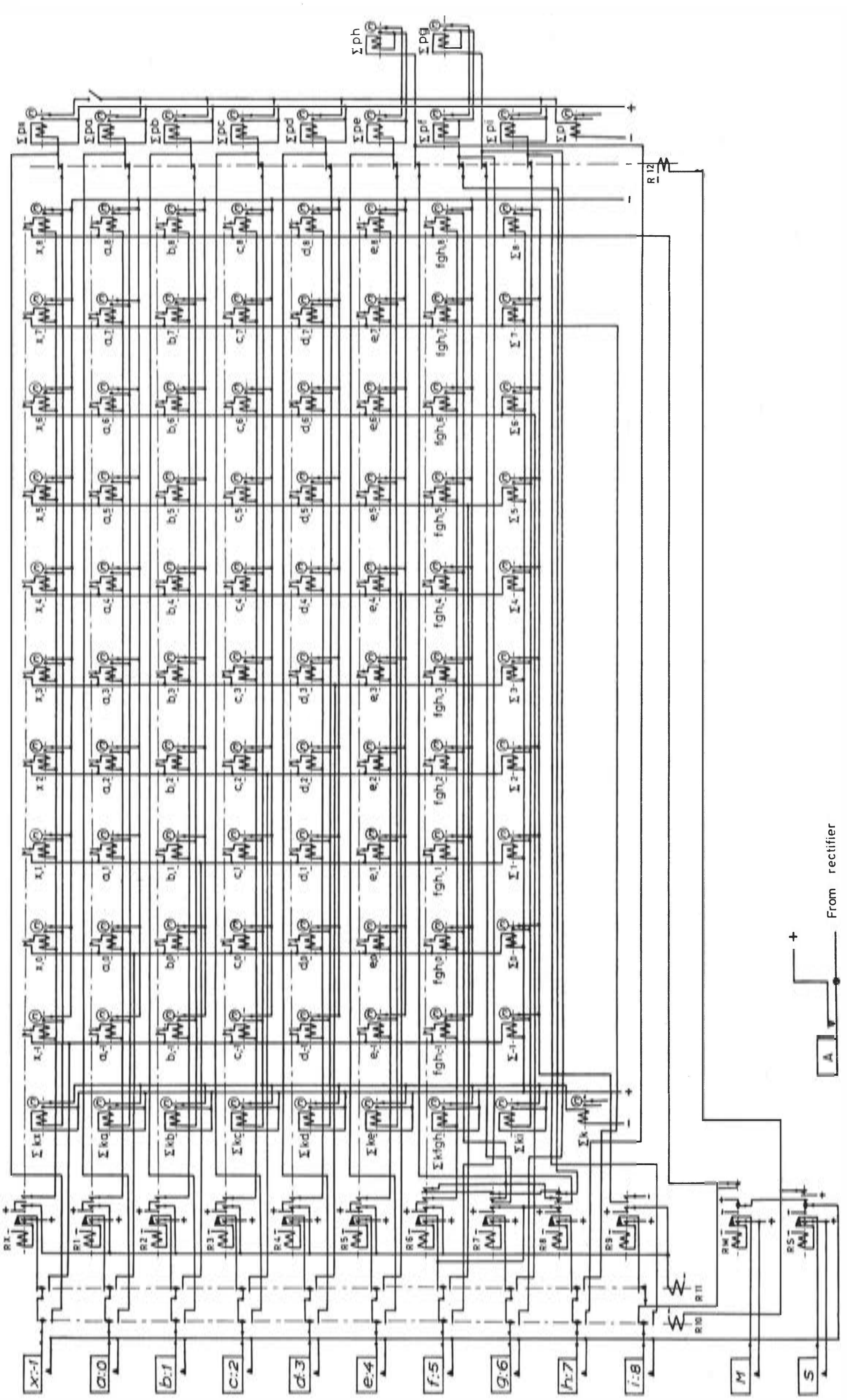


Fig. 14. Circuit diagram of the recorder. The objective indicator and the contact arrangement in the ocular are not included.

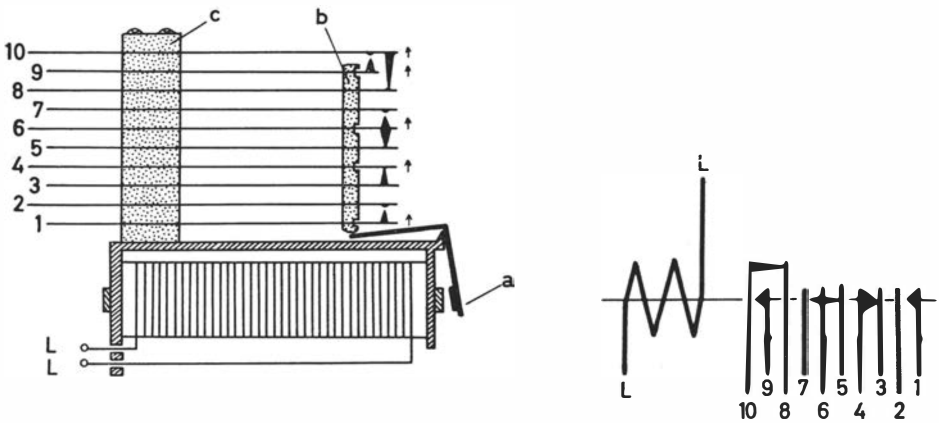


Fig. 15. Skeleton diagram of a relay and its corresponding diagram symbol.

coil of the electromagnet. By a lever mechanism the armature acts upon a number of contacts of different types, situated in two sets of contact springs on the upper side of the relay. By suitable combinations of contacts for "make", "break", "change-over" and "make-before-break" the current can be fed into the desired circuits.

Fig. 15 shows a skeleton diagram of a relay and its corresponding diagram symbol. When a current pulse is passed through the coil of the electromagnet, the armature (a) is attracted by the magnet, and the relay is operated. In this process the upper part of the armature is turned upwards, and raises a bar (b) consisting of an insulating material. In an insulated holder on the upper side of the relay, a set of contact springs with the springs numbered 1–10 is mounted (c). The flat springs 1, 4, 6, and 9 are fixed to the bar, and are therefore raised, whereas the other flat springs are not immediately influenced, since the bar passes through holes in these springs.

In operation the make-contact on spring No. 1 is raised towards spring No. 2, and a circuit is closed. The break contact on spring No. 4 is raised from the contact on spring No. 3, and the circuit is interrupted. When a "change-over" is effected, one of the contacts on spring No. 6 is raised from spring No. 5, and the connection between the springs 5 and 6 is interrupted. Spring No. 6 is raised further, the contact on its upper side touches spring No. 7, and the circuit is closed between them. When the relay is not operated, the springs 8 and 10 are connected by the contact on No. 10. In operation a circuit is closed, when spring No. 9 with its contact is raised towards spring No. 10 which is pressed upwards by the contact on spring No. 9 during the continued rise. Thereby the circuit is interrupted between the springs 8 and 10, and a "make-before-break" switching has been brought about.

When the current through the coil of the electromagnet is cut, the magnetic effect ceases, and under the pressure of the flat springs the armature returns to its position of rest.

A dot on a movable contact spring on the diagram symbols indicates that the spring is movable at the operation of the relay. For each relay a thin line of short dashes is drawn through the median line of the relay and through the contacts that are influenced by the relay.

The pulse counter

The single recordings take place in pulse counters, so-called subscriber's meters, of the standard type GM-2792/1500 used by the Swedish Telecommunications Administration. Such a pulse counter consists of an electromagnet, a five-digit drum, a zero-setting device, and a make-contact. When a current

Fig. 16. The diagram symbol of the pulse counter.

is passed through the coil of the magnet, an armature is attracted by the magnet. This, in turn, acts upon a make-contact which closes a circuit. On the cessation of the current through the magnet coil the armature returns to its position of rest. During this movement the drum turns one step forwards. At the same time the make-contacts separate, and the circuit is interrupted. The diagram symbol of the pulse counter is given in Fig. 16.

Diagram description

The principles of the functioning of the apparatus are most easily explained with the aid of the circuit diagram and a few examples of different recording procedures. For the sake of simplicity the recording of minerals as well as of grain-sizes is performed by hand in these examples.

In automatic grain-size recording with the measuring-ocular the apparatus functions in the same way as in altogether manual recording, the only difference being that in automatic recording no key for a certain grain size is depressed on the keyboard. The measuring-ocular has a contact device that is connected in parallel with the keyboard contacts x: – 1–i: 8. When the size of a grain has been established, the key K on the keyboard is depressed. A contact corresponding to the grain size in question is switched on, and a signal is carried through the apparatus in the same way as if the corresponding keyboard contact had been switched on. Connections between crossing conductors are marked with dots in the diagram.

A. Recording of a grain of mineral *a* in the third grain-size class

The key *a*: 0 is depressed. The vertical line farthest to the left in the circuit diagram carries positive voltage from the relays RS and RM. This voltage is now conducted to the relay R1 which comes into action. The make-before-break contact in R1 conducts current to the magnet-coil in R1, and R1 remains operated. The first make-contact in R1 conducts current to R11 with its change-over contacts, and R11 is operated. The pulse counters in row *a* receive positive voltage from the second make-contact of R1, and are simultaneously connected to their respective vertical lines in the rows – 1–8, when a series of contacts in R1, one for each vertical row, are closed at the operation of R1.

The transposition key M is depressed, the relay RM is operated, and remains so as a result of the current to the coil from the make-before-break contact. The change-over contact in RM now feeds the vertical line farthest to the left with negative voltage.

When the key *d*: 3 is pressed down, the negative voltage is conducted over the actuated change-over contact in R11 to the vertical line in row No. 3, and the pulse counters *a*, 3 and $\Sigma 3$ are operated. Through the make-contacts now closed in *a*, 3 the pulse counters Σka and Σpa receive current and operate, the make-contacts in them close, and current is conducted to the pulse counters Σk and Σp which operate.

The recording is now finished, and by depressing the resetting key A the current supply to the entire recorder is cut. The relays that are operated return to their positions of rest, and a new recording can be made.

If several grains in succession consist of the same mineral, it is not necessary to press the resetting key after each recording. When the key for the mineral in question has been depressed once as well as the transposition key M, the grains can be recorded in turn by depressing the keys for the proper grain-sizes only. No pressure on key *A* is required unless a new mineral appears.

B. Recording of a grain belonging to one of the mineral *f*, *g*, or *h*, e.g. a grain of the mineral *g* in the grain-size class 5

The key *g*: 6 is depressed, the relay R7 is operated, and remains operated by itself. From an actuated make-contact in R7 a current is conducted to R6 which is operated, and remains so by itself. In R6 a make-contact is closed which conducts current to R11 with its change-over contacts, and R11 is operated. Positive voltage is carried from another make-contact in R6 to all the counters in row *fgh*. A series of make-contact processes have furthermore taken place in R6, one for each vertical row, and thus positive voltage reaches each vertical row – 1–8. The pulse counter Σpg is under positive voltage which is carried through a make-contact in R7 to one of the make-contacts in the counters *fgh*, – 1–*fgh*, 8.

The transposition key is depressed, RM is operated, and remains so by itself, the change-over contact now conducts negative voltage to the vertical line farthest to the left.

The key *f*: 5 is depressed, and the negative voltage is carried to the vertical line No. 5; the counters *fgh*, 5, Σ 5, and Σ*kfgh* are fed with current, and operate. When the make-contact in *fgh*, 5 is actuated, current passes through Σ*pg* which operates. The make-contact in Σ*pg* is closed, and allows the current to pass through Σ*p* which operates in its turn. There is also operation in Σ*k*, as the current is carried to this counter at the closing of the make-contacts of Σ*kfgh*.

When finally the resetting key *A* is depressed, the apparatus is made ready for a new recording.

C. Recording of grains belonging to the mineral *i* and e.g. the grain-size class 7

The grain-sizes of the mineral *i* are recorded directly in the summation row $-\Sigma$ 1–Σ 8, and the mineral *i* thus has no row of counters of its own for the different grain sizes.

The key *i*: 8 is depressed, R9 is operated, and remains operated by itself, the first make-contact in R9 is closed, and R11 with its change-over contacts receives current, and is operated. The second make-contact of R9, which is now actuated, carries negative voltage to one of the make-contacts in the counters Σ – 1–Σ 8.

When the transposition key M is depressed, RM is operated, and remains operated, negative voltage is carried to the vertical line farthest to the left.

When the key *h*: 7 is depressed, the negative voltage is carried over an actuated change-over contact in R11 to the counter Σ7 which is always connected with the positive pole. Σ7 is now operated and the make-contact is closed. Current is then carried through the counter Σ*pi* and Σ*ki* which operate, and also actuate their make-contacts, and thus the counters Σ*p* and Σ*k* get current, and operate.

Finally the apparatus is made ready for a new recording by depressing the resetting key *A*.

D. Recording of a grain consisting of several different minerals

In the usual way one depresses in turn key *x*: – 1, transposition key *M*, the key corresponding to the grain size, and the resetting key. The connection process is the same as in case A with the exception that the counter Σ*p* does not operate when the make-contact of Σ*px* is actuated, because the connection between Σ*p* and the make-contact of Σ*px* is interrupted by a manually controlled contact near the counter Σ*px*. If this contact is closed, the upper row of counters has the same functions as the rows for the minerals *a–e*.

The size of the grain has now been recorded, but not so the different minerals contained in the grain. For the recording of the minerals one depresses key S. Then RS is operated, and remains operated by itself, the change-over contact in RS carries negative voltage to the vertical line farthest to the left. A contact in RS that is now operated carries positive voltage to R10 with its series of change-over contacts and to R12 with the series of break contacts, and both R10 and R12 are operated.

If e.g. the mineral *c* is to be recorded, one depresses the key *c*: 2. The negative voltage is then carried over a change-over contact actuated in R10 to Σpc which is always connected with the positive pole. Σpc is operated, and also actuates its make-contact, thus supplying current to, and operating Σp. When the key *S* has been depressed, several separate mineral recordings can be made immediately after each other.

Pressure on the resetting key A makes the apparatus currentless, the relays return to their positions of rest, and the apparatus is ready for new types of recordings.

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